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A Test of the MUCOOL RF Solenoid at Fermilab

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The solenoid for testing 805 MHz RF cavities in a magnetic field was shipped to Fermilab from Livermore in the spring of 2000. The magnet traveled over 2000 miles to Fermilab by truck. The superconducting magnet was installed in a shielded cave in Lab G at Fermilab. Much of the time between March 2000 and September 2000 was devoted to the installation of the power supply, the cables to the magnet, the system to feed liquid cryogens to the magnet, and the system that delivers lead gas to flow meters outside of the cave. The magnet vent system was set up so that all gasses from the magnet are vented outside of the lab G building.

Changes in the Experimental Setup

A pair of relief valves that relieve at 15-psi replaced the single 10-psi relief valve used for the Livermore test. The rupture disc installed at Wang NMR was replaced by a more robust rupture disc with the same 25-psi rating. The pair of relief valves and the rupture disc were discharged into a line that left the cave and the Lab G building. The gas from the leads was vented through rotometer type of flow meters. The oxygen level in the air in the cave was monitored.

The power cables and instrumentation cables were run from the cave through a hole in the roof. The cable run for the magnet was three to four times longer than it was at Wang's shop in Livermore. The power cable cross-sectional area was about twice that of the Livermore cables. The voltage drop through the cables and power supply diodes is about double that observed during the Livermore tests. Additional instrumentation was added for the Fermilab magnet setup. The following things are monitored by computer during magnet operation; 1) the liquid level in the magnet cryostat helium tank, 2) the liquid level in the nitrogen tank in the magnet cryostat, 3) the liquid level in the helium supply dewar, 4) the temperature at the tip of the helium supply line, and 5) the temperature at the downstream end of the insulator for each of the four lead gas circuits. This information can be logged and plotted from a web site at Fermilab.

Some Magnet Training History

The RF solenoid had been previously tested at Wang NMR Incorporated in Livermore California[1]. The magnet trained during the Livermore tests. It became clear that training was potentially a serious problem by the third quench during the September 1999 magnet test. During November 1999, individual coils were trained to above 270 A. As the magnet charged, there was considerable popping from the coils well before they quenched. The popping occurred when the coil reached new strain levels, but not when the magnet was held at a constant current or was going down in current. The magnet was trained in the gradient mode during November and December 1999, and January 2000. The magnet operated in the gradient mode at currents as high as 276 A (104 percent of design current), once the magnet was trained in this mode. Magnetic measurements were done at various currents when individual coils were tested and when the magnet operated in the gradient mode. The magnetic measurement consisted of measuring the field on axis with a Hall probe. At high magnetic fields the Hall probe saturated so errors up to 3 percent were observed. Magnet quenches blew gas through the single 10 psi relief valve and the gas cooled leads, but the 25 psi rupture disc did not break.

Solenoid mode training was done in September 1999, December 1999, and January 2000. The magnet never reached its design current of 230 A in the solenoid mode during any of the Livermore tests. The highest current achieved in the solenoid mode at Livermore was 214 A (about 93 percent of the magnet design current in this mode). At the conclusion of the Livermore tests in January 2000, it was thought that it would be difficult to operate the magnet in the solenoid mode much above 80 percent of its design current of 230 A. The training history for the Livermore RF solenoid tests is documented in References [1] and [2]. The magnet design is discussed in Reference [3]. Magnetic measurements were made while the magnet operated with single coils alone, in the gradient mode and in the solenoid mode[1,2]. The saturation of the Hall probe was most evident in the solenoid mode measurement[1].

Not all that was learned in the Livermore tests was bad. We learned a full nitrogen tank can be expected to last about two days once the magnet is completely cold. We could not determine the boil off for the helium tank in the cryostat. The calculated boil off rate for the magnet cryostat with the helium transfer line removed was estimated to be about 2.7 liters per hour for a 4.2 K heat leak of 1.9 W. Most of this heat leak comes down the four 300-A gas-cooled current leads. Most of the tests at Livermore were done with low liquid levels in the helium tank. During one quench, the liquid level was below the bottom of the magnet. We found that the magnet tolerates operation at low liquid levels very well. We also found that we could save liquid helium by training the magnet at low helium levels in the cryostat.

The quench protection diodes in the power supply appeared to work well. It was apparent that a quench in one coil would heat up the other coil even if it was not powered. When both coils were powered, the coil that quenched was hotter than the coil that didn't quench, but both coils were quite warm. Quench-back appeared to be part of the quench protection mechanism.

The September 2000 Fermilab Test

Because of the magnet's previous training history, it was expected that considerable training would be required at Fermilab in order to bring the magnet to near its design current in either operating mode. We were wrong in this assessment. There were no quenches below the design current in either mode during the Fermilab solenoid tests of 26 through 29 September 2000.

There were a couple of changes in the magnet set up at Fermilab compared to Wang NMR in Livermore. 1) At Fermilab, the helium dewar was well away from the magnet cryostat. There were no magnetic forces between iron in the helium dewar and the magnet. 2) The magnet cryostat was farther from the floor at Fermilab. Again, magnetic forces are lower. 3) The forces from the iron in the area was more balanced at Fermilab than at Livermore. 4) There was no flow from the helium dewar into the magnet cryostat anytime the magnet was run at Fermilab.

The groaning and popping sounds characteristic of the training observed during the Livermore tests were almost completely absent during the Fermilab tests. Because we expected to have to train the magnet, all of the tests were done with low liquid helium levels in the cryostat. This may have contributed to the magnet quenching that did occur.

The RF solenoid magnet was shipped to Fermilab warm (about 300 K). The magnet remained warn until the week of the18 September 2000. During this week the cryostat and the magnet were cooled to 77 K using liquid nitrogen. The magnet was then cooled to 4.2 K using liquid helium. The transfer line system is permanently attached to the magnet. The line between the helium dewar and the cryostat can be shut off while the magnet is operating. The nitrogen shield was kept cold for a couple of days before the magnet was tested. When the helium cool down was started on 26 September 2000, the magnet temperature was about 85 K. The cool down from 85 K to 4.2 took about 4.5 hours.

The magnet test runs are summarized below. The first 20 runs of the magnet were performed in Livermore[1]. Run 21 is a continuation of the quench history for the RF solenoid.

Run 21 Coil 1 was hooked up so that it could be charged alone. The charge voltage was set at 5.0 V at the power supply. The magnet quenched at 271 A on the power supply meter. The actual current magnet current could have been above 280 A. Based on the power supply current $E_q = 1.54$ MJ and $B_q = 4.66$ T. The was virtually no coil popping as the magnet charged. It is not clear whether the quench that occurred was due to training. At the time of the quench, the cryostat contained only about 20 liters of liquid helium. There was barely any liquid helium touching the magnet coils.

Run 22 Coil 2 was hooked up so that it could be charged alone. The charge voltage was set at 5.0 V at the power supply. The magnet reached 270 A as read on a separate meter. Based on the separate meter current $E_o = 1.52$ MJ and $B_o = 4.64$ T. The coil charged to 270 A in about 55 minutes. The magnet was discharged in 94 minutes. There was no coil popping observed. No magnetic measurements were made.

Run 23 Coils 1 and 2 were hooked in the gradient mode and charged to 274.1 A (103.4 % of design current) at 5 to 6 V without quenching. Eo = 2.57 MJ and Go = 24.8 T/m. There was no popping in the coil. The magnet was charged to 265 A in 92 minutes. No magnetic field measurements were made.

Run 24 Coils 1 and 2 were hooked in the solenoid mode and were charged at 5 to 6 V with current holds at 184 A, 230 A and 253.4 A. The magnet quenched during the hold at 253.4 A (at 110.2% of design current). Eq =3.15 MJ and Bq = 5.51 T. Resistance measurements suggest that coil #2 caused the quench. There was virtually no coil popping. The total time from 0 to 253 A was 296 minutes with holds of 47 minutes and 95 minutes. At the time of the quench, there was less than 10 liters of liquid helium in the cryostat and no liquid helium was touching the magnet coils. From the 8 minute hold time at 253.4 A, it appears unlikely that this magnet quench was a training quench. No magnetic field measurements were made.

Run 25 Coils 1 and 2 were hooked in the solenoid mode and charged at 7.5 V to a current of 234.0 A (at 101.7% of design current) with no quench. Eo =2.69 MJ and Bo = 5.08 T. The charge from 0 to 231.5 A took about 72 minutes. There was no coil popping. There was about 32 liters in the cryostat at the end of the charge. No magnetic field measurements were made.

Run 26 Coils 1 and 2 were hooked in the gradient mode and the magnet was charged at 7.5 V. The current settled down in the current control mode at 270.2 A (at 101.9% of design current). Eo =2.50 MJ and Go = 24.5 T/m. It took 59 minutes to charge 0 to 270.2 A. There was no popping in the coils. There was about 34 liters of helium in the cryostat at the end of the charge. No magnetic field measurements were made.

Run 27 This run is an extension of Run 26 with the coils in the gradient mode. The magnet quenched at 294.0 A (110.9 % of design current). Eq = 2.96 MJ, Gq = 26.6 T/m. The magnet charged from 270.2 A to 294.0 A in about 40 minutes. There was virtually no popping in the coil while it charged. Just before the quench, the cryostat contained about 32 liters of liquid helium. This quench does not appear to be a training quench.

It appears that none of the quenches that were observed during the Fermilab test were caused by magnet training. The popping that was heard during charging at the Livermore tests was almost non-existent during the Fermilab test of the magnet. The lack of apparent training can be seen in Figures 1 and 2 on the next page. Figure 1 compares the current reached in all twenty-seven runs. It is clear that the currents in all of the Fermilab runs were above design current for the magnet. Figure 2 compares the stored energy reached in all of the runs. The peak quench stored energy in the solenoid mode was 3.15 MJ. The peak stored energy reached in the gradient mode was 2.96 MJ. In both cases this stored energy was dumped into the coils and the aluminum magnet bobbin. All three quenches were quite mild, because all of the helium gas generated by the quench was vented outside of the building.

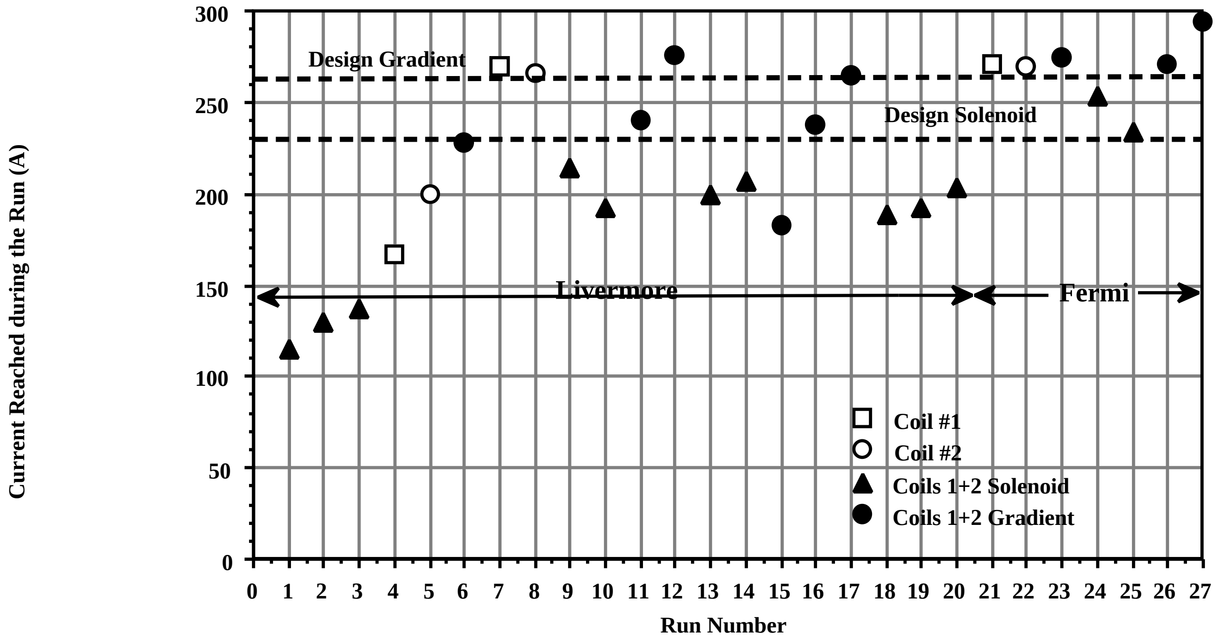


Figure 1. The Current Reached During all of the RF Solenoid Test Runs
(Runs 1 through 20 occurred at Wang NMR; runs 21 through 27 occurred at Fermilab.)

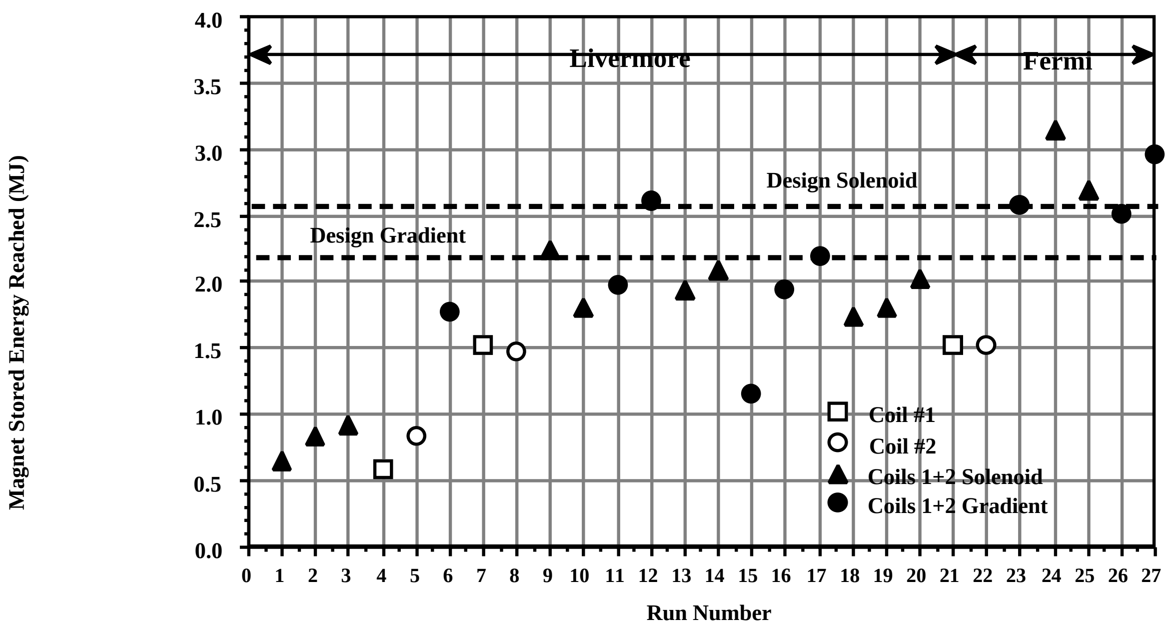


Figure 2. The Magnetic Energy Stored During all of the RF Solenoid Test Runs
(Runs 1 through 20 occurred at Wang NMR; runs 21 through 27 occurred at Fermilab.)

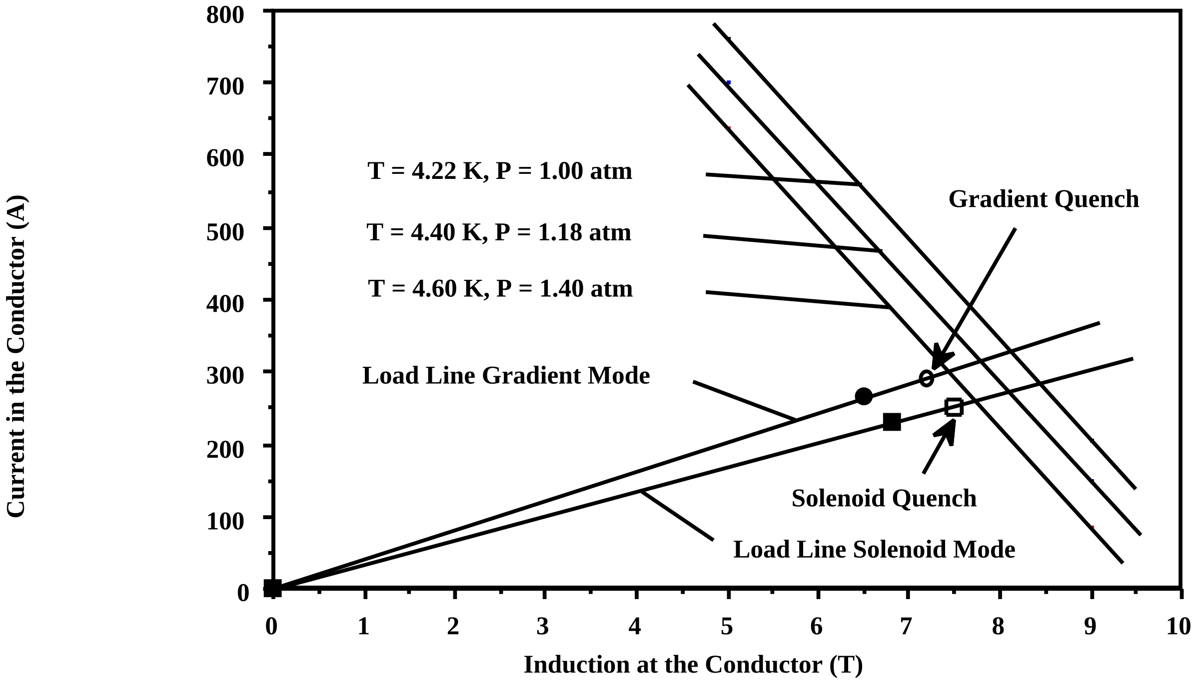


Figure 3. The Magnet Load Line for the Magnet in the Solenoid and Gradient Modes And the Superconductor Critical current as a Function of Induction and Temperature (Note: the solid square and circle are the design points for the magnet. The open square and circle are the quench points above 110 percent of design current.)

Figure 3 above shows the conductor critical current as a function of temperature and magnetic induction. The load lines for the magnet in both modes are also shown. The solid square and circle are the design points for the magnet in the two modes. In runs 24 and 27, the magnet quenched at a current about 11 percent above the design current along the load line. Given the behavior of the magnet during all of the Fermilab runs (runs 21 through 27) it is felt that neither of the quenches seen in runs 24 and 27 were training quenches. The arguments for this supposition are as follows: 1) The pressure in the magnet cryostat was above 1 atm, because of the pressure drop through the lead gas lines and the vent line. The cryostat pressure was not measured. 2) There was little or no evidence of the popping in the magnet that had occurred during the training runs at Wang NMR in Livermore. 3) The quench in the magnet operating in the solenoid mode at 253.4 A occurred after the magnet sat at that current for 8 minutes. This behavior suggests that the magnet was warming up. 4) The liquid helium level in the cryostat was low during all of the quenches. There was no liquid helium touching the magnet coils during run 24 when the magnet was in the solenoid mode. There was very little helium touching the lower part of the coil during Run 27 when the magnet quenched in the gradient mode at 294.0 A. The Run 21 quench may have also occurred at an elevated temperature.

One can make a case for the magnet temperature (in the high field point in the upper part of the coil) could have been above 4.6 K due to lack of helium cooling and elevated pressure in the cryostat. The only way to resolve whether the quenches observed in runs 21 through 27 were training quenches is to repeat the quenches with only a few liters of helium in the magnet cryostat. Filling the cryostat with helium will ensure that the magnet temperature is uniform throughout the magnet, so one must repeat the quench experiment at low liquid level. A measurement of the pressure in the helium vessel of the cryostat will allow one to know the temperature of the helium in the magnet cryostat. Since the magnet can operate at 110 percent of design current in both modes, it is not recommended that we continue to quench the magnet.

The Livermore tests clearly showed magnet training. The magnet did not remember its training very well, while at Livermore. When the magnet was warmed up, it retrained, but it appeared to have not lost all of its previous training. When the magnet was shipped to Fermilab, retraining was expected, particularly in the solenoid mode. At Livermore, the magnet trained better in the gradient mode than in the solenoid mode, despite the fact that in the gradient mode the coils were being forced apart by a 3.0 MN (about 300 metric tons) force.

The question that one should ask is what was different at Fermilab compared to Livermore. The following changes occurred between the Fermilab and Livermore runs: 1) The magnet was shipped over 2000 miles on a truck. The shipping may have loosened the coils. 2) At Livermore, the helium supply dewar was close to the magnet cryostat. Iron in the helium dewar caused a non-symmetrical magnetic force on the coils. 3) At Livermore, the magnet coils were close to the floor and to concrete walls. The iron-reinforcing bar in the floor and the walls could contribute to the production of non-symmetrical magnetic forces. 4) Helium in the supply dewar is completely isolated from the helium in the cryostat. This means there is no flow of helium between the two vessels that might have put heat into the magnet. The best guess as to what caused training at Livermore was the asymmetrical forces caused by nearby iron. These forces may have moved the coils. We may never know what really caused the training at Livermore.

The Cryogenic Performance of the RF Solenoid during the Fermilab Test

When the magnet was tested at Wang NMR in Livermore California, we could not measure the boil off rate from the helium cryostat. During the Livermore tests, the helium supply dewar was kept connected to the magnet cryostat. One could not shut off helium flow between the supply dewar and the magnet cryostat. During magnet test at Livermore, the liquid level in the cryostat would rise because the supply dewar would become pressurized and liquid would be transferred to the magnet cryostat. During a magnet quench, some of the helium in the cryostat would be forced back into the supply dewar by a higher pressure in the cryostat. Nitrogen boil off was measured during the Livermore test. Once the magnet was entirely coil and had been cold for two days, the 17.5-liter nitrogen tank would last about two days. The estimated boil off rate was about 0.4 liters per hour for an estimated heat leak into the shields of 18 W.

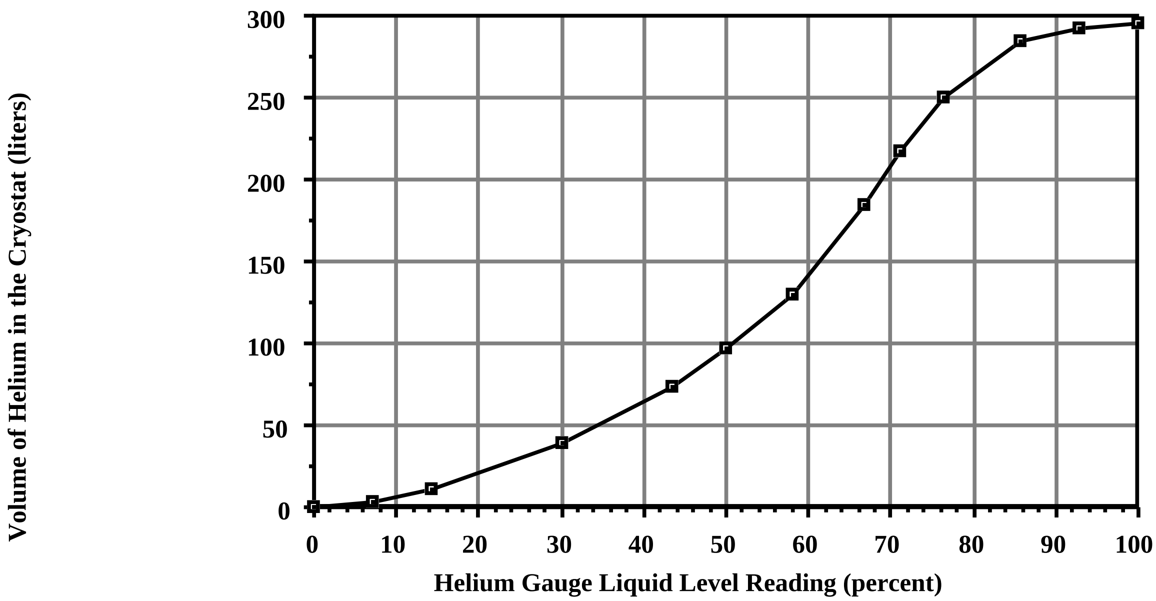
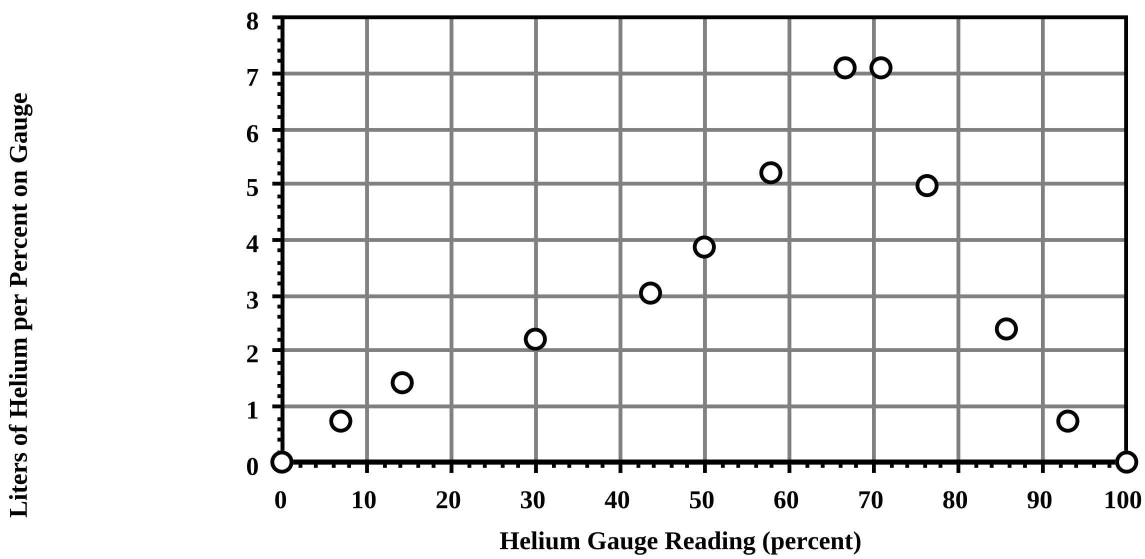


Figure 4. The Number of Liters in the RF Solenoid Cryostat



As a Function of the Liquid Level

Figure 5. The Amount of Helium per Percent of Gauge reading as a Function of Liquid Level

Figure 4 and Figure 5 above show that the amount of helium in the cryostat tank is not linear reading on the helium level gauge. The reasons for this are as follows: 1) The helium tank is a cylinder on its side with another cylinder on its side inside to the tank. The inner cylinder is not concentric with the outer cylinder so two thirds of helium volume is above the halfway point in the tank. 2) The helium level gauge is curved. It hugs the wall of the outer cryostat cylinder.

From Figure 4 one can calculate the helium consumption while the magnet is operating if one knows the gauge reading as a function of time. The helium consumption was calculated based on changes in the liquid level for various times during the Fermilab tests. The following helium consumption was calculated: 1) On 27 September 2000 from 14:30 to 16:00, the consumption was 3.5 liters per hour (heat leak = 2.5 W) as the coil was being charged and discharged. 2) On 27 September 2000 from 16:22 to 17:42 while the magnet was charging the consumption was 5.8 liters per hour (Q = 4.1 W). 3) On 28 September 2000 from 9:45 to 12:00, the consumption was 3.7 liters per hour (Q = 2.6 W). 4) On 28 September 2000 from 12:00 to 14:53 when the current above was 230 A, the consumption was 3.6 liters per hour (Q = 2.5 W). 5) On 29 September 2000 from 10:10 to 11:47, the helium consumption was about 3.9 liters per hour (about 2.7 W). There are a number of errors that could affect the helium consumption calculations.

Three over night boil off measurements were also made without current in the coils: 1) On 26 and 27 September 2000 from 15:51 to 1:40, the estimated helium usage was 3.9 liter per hour (Q= 2.75 W). 2). On 27 and 28 September 2000 from 17:08 to 6:28, the estimated usage was 2.9 liters per hour (Q = 2.03 W). 3) On 28 and 29 September 2000, from 15:25 to 3:51 the helium usage was about 3.0 liters per hour (Q = 2.1 W). There is almost no difference in the last two estimates. On the first night, all of the helium went up the gas-cooled leads. On the other two nights, some of the helium gas flow went out the by-pass valve to cool the neck.

From the helium measurements done to date while the magnet is operating, it is clear that when the tank is full (with 295.5 liters in it) the magnet can operate for at least 69 hours (almost 3 days) without refilling the helium tank. It appears that the actual magnet cryostat heat leak is within 10 to 15 percent of calculated value.

Measured liquid nitrogen levels at Livermore suggest that the nitrogen tank will last about two days if the magnet has been cold for some time. The data for the Fermilab test is as follows: 1) On 27 September 2000 from 14.02 to 17.42, the nitrogen consumption was about 1.28 liters per hour (Q = 53 W at 77 K). On 28 September 2000, from 9:40 to 14:41, the nitrogen consumption dropped to 0.54 liters per hour (Q = 22 W at 77 K). On 29 September 2000, from 10:30 to 12:00 the nitrogen consumption was about 0.39 liters per hour (Q = 16 W at 77 K), which is close to the value measured in Livermore. It is clear that it takes several days for the liquid nitrogen boil off to come to equilibrium once the magnet has been cooled to liquid helium temperature.

Power Supply, Voltage Drop, and Current Issues

The voltage drops in the power supply, the current cables and the diodes were different when the magnet was operated at Fermilab as compared to when the magnet operated in Livermore. The diodes and power supply were the same for both sets of runs, but the cables were more resistive at Fermilab. Figure 6 shows the voltage drops for the two single coil runs at Fermilab; Figure 7 shows the voltage drops for the solenoid and gradient two-coil runs at Fermilab.

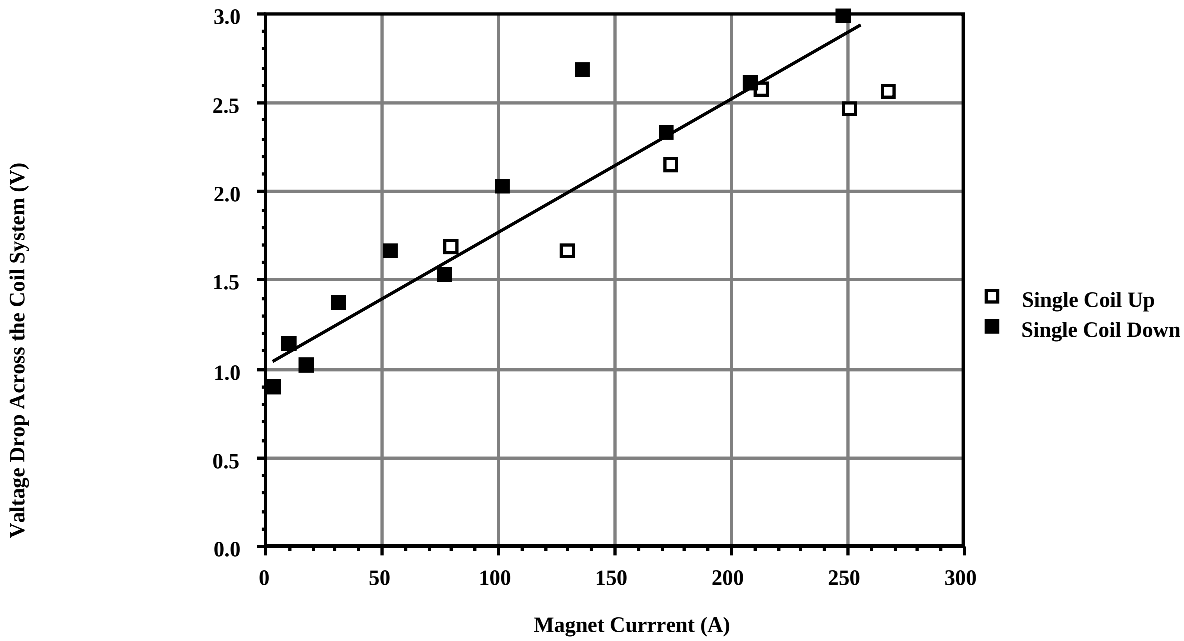


Figure 6. Voltage Drop across the Power Supply Diodes and Cables as a Function of Current During the Two Single Coil Runs (Runs 21 and 22)

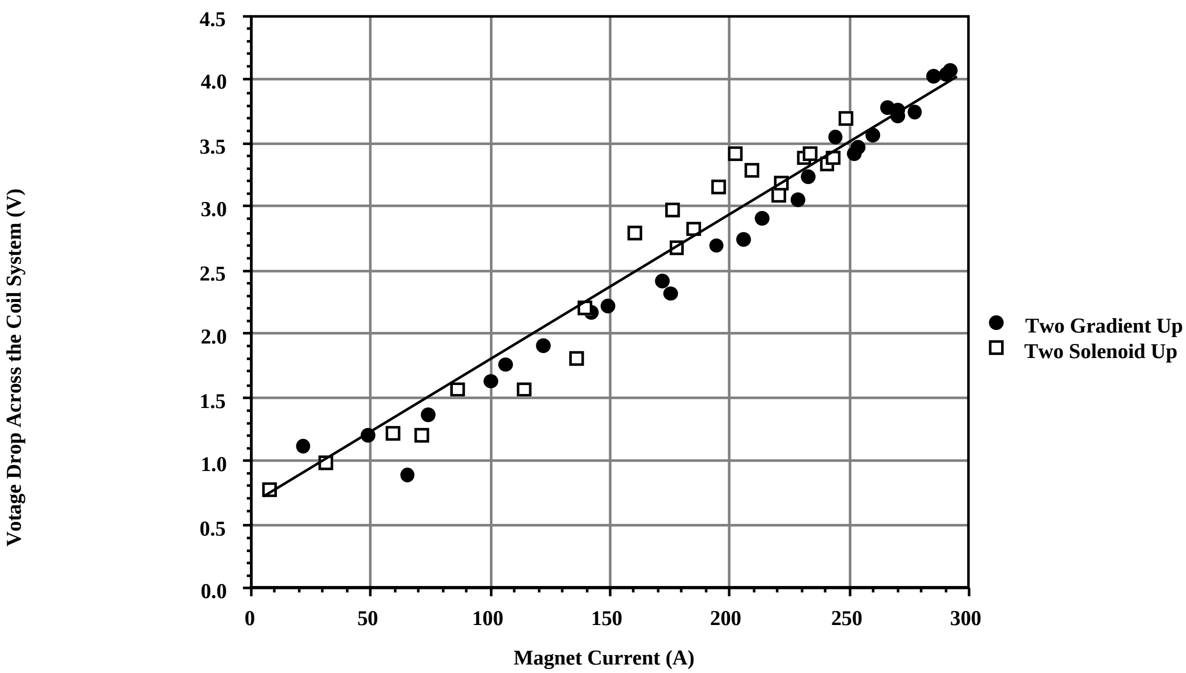


Figure 7. Voltage Drop across the Power Supply Diodes and Cables as a Function of Current And Coil Hookup Mode for the Two-Coil Runs (Runs 23 through 27)

The voltage drop for a single coil was between 2.5 and 3 V including the diodes in the power supply. Within the scatter of the points the voltage going down was not much different from the voltage going up. The voltage drop for two coils is approximately the same whether the coils are hooked in the solenoid mode or the gradient mode. The voltage drop across the system is over 4.0 V when the current is 300 A. The scatter in the data is due to a couple of factors, such as not knowing the current change rate to more than a few percent. In some cases the time change per current step was not accurately known. There are probably other sources for the voltage drop scatter shown in Figures 6 and 7. It appears from the Figure 6 that the cable resistance and internal power supply resistance for a single coil is about 8.1 m-ohm. The cable and power system resistance for two coils hooked in series is about 11 m-ohm. This suggests that the cables from the power supply to and from each magnet have a resistance of about 3 m-ohm

During the Fermilab test it was observed that the current meter on the power supply was inconsistent. The current would go up as the magnet charged. Then the meter reading would decrease even though the magnet was still charging. A clip-on amp meter was put around one of the cables leading from the power supply to the magnet. Depending on the run there was considerable discrepancy between the clip-on meter and the power supply amp meter. During a typical run, the amp meter on the power supply would read high at the start of the charge. In the mid-range of magnet current (say 80 to 160 A), the two meters agreed within an ampere or two. As the magnet pushed to higher currents (above 200 A), the current reading on the power supply was usually lower than the current read by the clip-on amp meter. At high currents the discrepancy between the clip on meter and the current meter on the power supply was often larger than 10 amperes. During the first run at Fermilab (Run 21) coil #1 quenched at 271 A. This current may have been over 280 A. Subsequent runs were made using the clip-on meter to measure the current. Heating from the power supply appeared to be a factor on how well the power supply amp meter performed. Cooling using an extra fan appeared to help improve the accuracy of the power supply amp meter.

Recommendations for Changes in the RF Solenoid Systems

The RF solenoid cryogenic system operates adequately. The heat leak into the magnet cryostat is within 10 to 15 percent of the calculated heat leak. The RF solenoid can be cooled down and operated by trained Fermilab cryogenic technicians that do not have to be present for 24 hours a day. Several changes in the cryogenic system are recommended. In order of importance, these changes are: 1) The magnet cryostat should have a pressure gauge or a pressure transducer. Knowing the pressure in the cryostat means that one knows the temperature of the helium in the cryostat. If a transducer is installed, the cryostat pressure can be monitored remotely and it can be graphed as a function of time. 2) A line that carries helium gas from the cryostat neck should be installed. A gas flow meter and control valve should be installed in the line from the cryostat neck so that the neck flow can be controlled in the same way as the lead gas flow. The flow from the neck should come from just up stream from the vent ball valve. A small flow of helium cooling the neck may reduce the cryostat heat leak. 3) A by-pass circuit could be installed on the helium transfer line at the point where it goes into the magnet cryostat. This allows the transfer line between the helium supply dewar and the magnet dewar to be pre-cooled before adding liquid helium to the magnet cryostat. This permits one to fill the magnet cryostat while the magnet is fully charged. This will save time during the RF experiment.

As a result of the magnet test at Fermilab a number of changes in the power supply and instrumentation circuits are recommended. In order of importance, they are: 1) Current shunts should be installed on both coil circuits. The volt-meters across the shunts should be hooked up so that both meters read a positive voltage drop when the magnet is in the solenoid mode. When the magnet operates in the gradient mode one meter should read positive and the other meter should read negative. As an example, a 1 m-ohm current shunt would have a reading of 300 mV at the full power supply current of 300 A. The shunt voltages should be logged with the data log system. 2) The power supply should have extra cooling fans installed so the power supply temperature can be brought down. 3) There should be a voltage tap at the top of each of the four magnet current leads. This permits one to read the coil charge voltage at the leads and monitor the voltage across the coils during a quench. 4) A coil discharge circuit would speed up the discharge of the coil. This could be an ordinary resistor that puts an additional 3 Volts across the coil at 250 A. (A resistance of 12 m-ohms will do the trick.)

Acknowledgements

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